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# Submillimeter studies of circumstellar disks in Taurus and Orion

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**Abstract.** We highlight two recent studies of circumstellar disks in the Taurus and Orion star forming regions. Using the JCMT and CSO, we measure disk fluxes in Taurus over a wide range of submillimeter wavelengths and determine the frequency dependence of the dust opacity. We find clear evidence for a systematic change in its behavior with time, most readily explained by grain growth. Using the SMA, we observed the protoplanetary disks (proplyds) in the Orion Trapezium cluster. The combination of high resolution, high frequency, and high sensitivity that this instrument provides made it possible to resolve disks from one another, distinguish their emission from background cloud material and surrounding ionized gas, and to detect thermal dust emission. This allowed us to make the first mass measurements of the proplyds and to assess their viability for planet formation.

## 1. Introduction

Circumstellar disks are an inevitable byproduct of the collapse of a molecular core to form a star or collection of stars because of the enormous compression of size scales and the consequent magnification of any slight initial rotation. These disks funnel material onto the star but they can also form planetary systems. We now know this not only from our own Solar System but the detection of more than one hundred planets around other stars. To help understand the mechanisms by which planets form, however, requires basic measurements of disk properties such as masses and sizes.

A great deal of work has been carried out in this area of course, including seminal papers by Beckwith et al. (1990) on dust masses derived from millimeter continuum fluxes, and Dutrey et al. (1996) on disk sizes from millimeter interferometry. Needless to say, the BIMA interferometer has also played a major role in disk studies (e.g., Looney, Mundy, & Welch 2000).

Here, we present recent work on measurements of basic disk properties in two quite different environments. Stars form mostly singly or in binaries in Taurus, but stars in the Trapezium cluster in Orion are much closer together and bathed in a strong ultraviolet radiation field. We have used the three submillimeter telescopes on Mauna Kea for these studies and have found that extending disk observations to submillimeter wavelengths can provide important new information. Certainly, here in Hawaii, we agree wholeheartedly that one telescope is never enough! A more formal writeup of this work is available in Andrews & Williams (2005) and Williams, Andrews, & Wilner (2005).

## 2. A submillimeter survey of Taurus disks

Submillimeter observations probe the cool, outer regions of circumstellar disks where giant planets are expected to form. Such long-wavelength data are required to infer the total masses of disks, and can also be used to study the collisional growth of dust grains into planetesimals via changes in the spectral dependence of the disk opacity. Comparisons of infrared observations with physical models of star-disk systems have led to a sequence of evolutionary stages that occur before the star arrives on the main sequence (Lada & Wilking 1984; Adams & Shu 1986; Adams et al. 1987). In the Class I stage, an extended circumstellar envelope is rapidly dumping material onto a central protostar and a massive disk. After the envelope is dissipated, the system becomes a Class II object, with a disk that is actively accreting material onto a central, optically visible star. In the final Class III stage, *at least* the inner part of the disk has been evacuated, although the dominant mechanism for this process remains in debate (see Hollenbach et al. 2000). The most interesting possibility is that the gas and dust in the disk have agglomerated into larger objects in a developing planetary system. The disk evolution scheme highlighted above is based on the shape of the infrared spectral energy distribution (SED), and therefore focuses on the inner, warmer part of the disk. A comparable submillimeter survey could therefore reveal information about how disks evolve radially.

A single-dish continuum survey at 350, 450, and 850 $\mu$m of more than 150 disks in the Taurus star-forming clouds has recently been completed, using both the SCUBA array on JCMT and the SHARC-II camera on the CSO (Andrews & Williams 2005). The primary goal of that program was to take advantage of the stability and efficiency of the SCUBA instrument to obtain an 850 $\mu$m sample with a relatively uniform flux density limit of $\sim$10 mJy (3 $\sigma$), corresponding roughly to a detection threshold of disks with masses greater than that of Jupiter ($\sim 10^{-4}\,\mathrm{M}_\odot$). Compared to previous surveys at 1.3 mm (Beckwith et al. 1990; Osterloh & Beckwith 1995), the submillimeter observations are more sensitive by at least a factor of 5, and considerably more uniform.

To allow for optical depth effects and a radial temperature distribution in determining a disk mass, a simple disk structural model (e.g., Adams et al. 1987; Beckwith et al. 1990) was employed in fits to the full SED from the infrared through millimeter. An empirical calibration of the 850 $\mu$m flux density and the disk mass indicates that assuming optically thin emission at a temperature of $\sim$20 K is a reasonable means of measuring $M_d$ in the absence of sufficient SED information. Figure 1 shows an example of a SED generated from such a model, with two key regions marked: the mid-infrared and millimeter both are simple power laws in frequency. The infrared index, $n$, defines the different Classes of disk evolution (Greene et al. 1994), and the millimeter index, $\alpha$, constrains the dust grain opacity and thereby the maximum size of the grains (Pollack et al. 1994).

We were able to obtain short wavelength (350 and/or 450 $\mu$m) fluxes for all Class I objects and more than half of the Class II objects that were detected at 850 $\mu$m. Combining with tabulated fluxes at millimeter wavelengths from the literature where possible, we then measured the SED slope over a factor of $2-10$ in wavelength range. This allowed us to determine $\alpha$ more accurately than previous work and study its evolution.

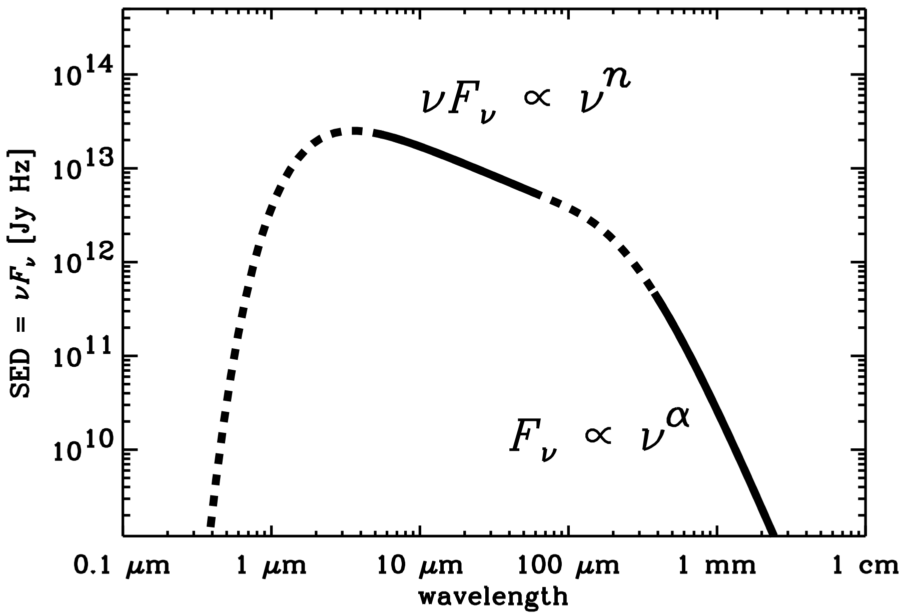


Figure 1. A spectral energy distribution generated from a simple disk model that assumes radial power-law distributions of both surface density and temperature. The solid regions of the curve are of particular interest for disk studies. In the infrared, the SED behaves as $\nu F_\nu \propto \nu^n$, and the index $n$ (essentially an infrared color) is a common diagnostic for evolution in the inner disk. In the submillimeter, the continuum spectrum follows $F_\nu \propto \nu^\alpha$, where the index $\alpha$ is set primarily by the spectral form of the disk opacity.

The major results of our survey are summarized in Figure 2. The mass in millimeter sized grains decreases from median values of $3 \times 10^{-2}\,M_\odot$ for Class I to $3 \times 10^{-3}\,M_\odot$ for Class II to $6 \times 10^{-4}\,M_\odot$ for Class III objects. The empirically measured millimeter spectral index also decreases from a median of 2.5 for Class I to 1.8 for Class II objects. This is the first time that the evolution of basic properties of the outer disk have been quantified and is due to the high sensitivity, large sample size, and extended wavelength coverage of the survey.

The millimeter spectral indices in Class I and Class II objects are considerably less than that found in the ISM, $\alpha_{\rm ISM} = 4$. The low values could be caused by high optical depth or a change in the frequency dependence of the dust grain opacity, $\kappa \propto \nu^\beta$. A simple radiative transfer calculation shows, in the Rayleigh-Jeans limit, $\alpha = 2$ for optically thick emission and $\alpha = 2 + \beta$ in the optically thin case. (A value lower than 2, as found for Class II objects, may be due to the Rayleigh-Jeans assumption being invalid for the short wavelength data or additional processes such as significant ionized gas emission at long wavelengths from a jet.) Our disk models, which integrate over the temperature and surface density radial profiles, indicate that no more than $\sim 20-40\%$ of the emission is optically thick at submillimeter wavelengths. We therefore conclude that $\beta$ for

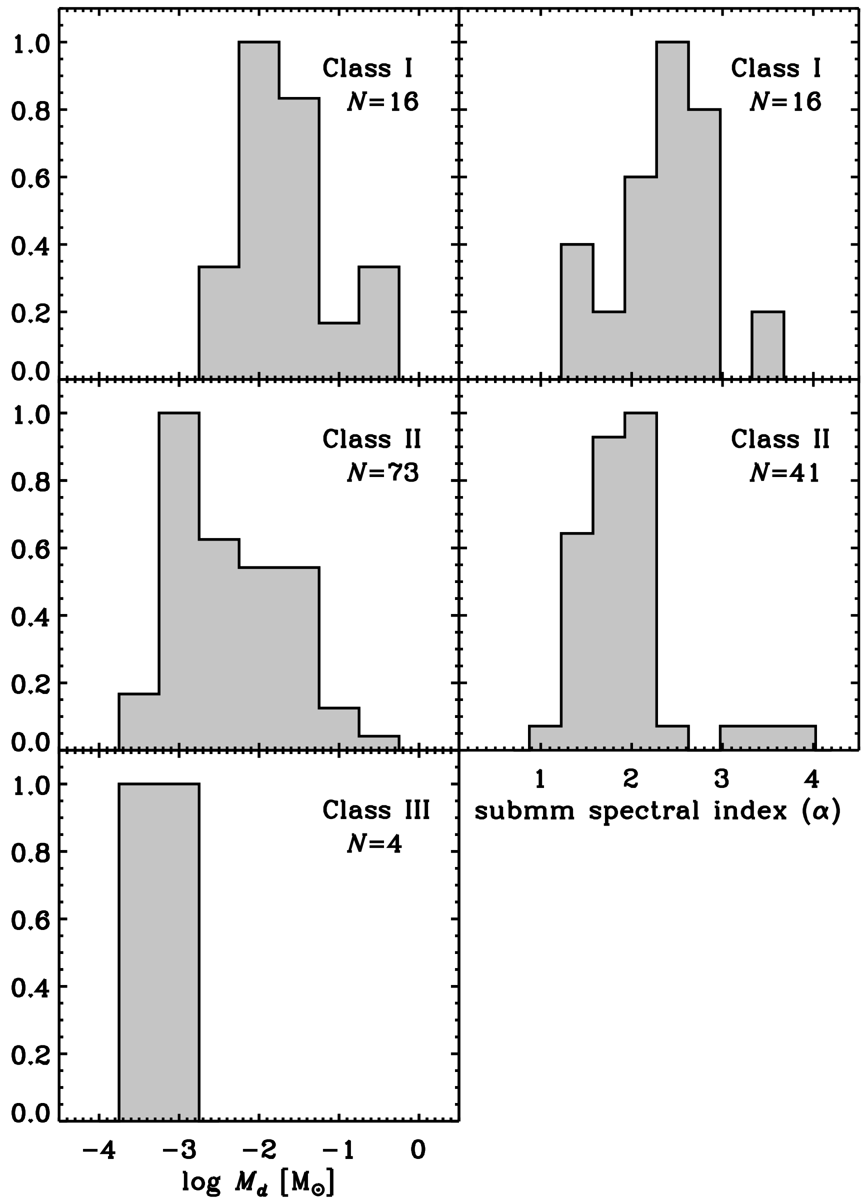


Figure 2. Histograms of circumstellar disk masses and submillimeter spectral indexes for different evolutionary states, derived from the JCMT-CSO survey by Andrews & Williams (2005). Each histogram has been normalized to a peak of 1 to emphasize the decrease in mass from Class I to II to III, and the decrease in $\alpha$ from Class I to II.

disk grains is not only substantially lower than for ISM grains (first noted by Beckwith & Sargent 1991) but that it also decreases as disks evolve from Class I to Class II.

Further evidence for an evolution of grain properties is shown in Figure 3. We found an inverse correlation between the infrared and millimeter spectral indices that can seemingly only be explained by a decrease in $\beta$. If the grain properties did not change, $\alpha$ would depend only on the disk structure. Typically assumed evolutionary scenarios such as viscous spreading or decreasing disk mass would lower the optical depth at all radii and increase $\alpha$, opposite to the observed trend. The empirical decline in millimeter spectral slope, $\alpha$, as disks evolve is due to a flattening of the dust opacity index, $\beta$, and is most readily explained by an increase in the maximum size of the grains (Pollack et al. 1994), from microns to millimeters. (See also the paper by David Wilner in this volume for evidence of growth to centimeter sizes in TW Hya.)

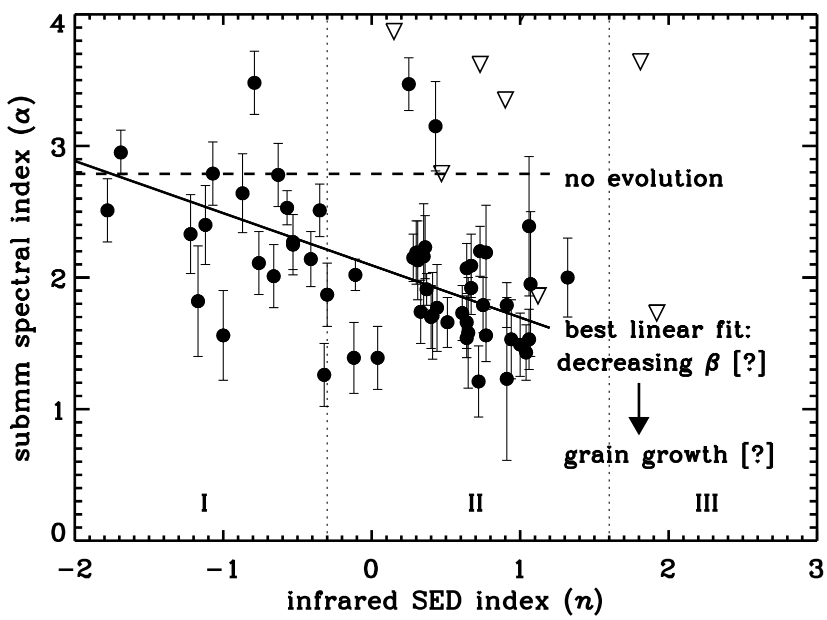


Figure 3. The behavior of the submillimeter spectral index, $\alpha$, as a function of the infrared SED index, $n$. The vertical dotted lines show the boundaries between different disk classifications based on Greene et al. (1994). Open triangles are 3 $\sigma$ upper limits. The dashed horizontal curve marks the expected behavior if basic disk properties do not evolve with time. Typical evolutionary behavior, like the viscous spreading of a disk or the loss of mass, leads to a decrease in the optical depth of the disk, and would therefore result in a trend in the opposite sense. The observed decrease of $\alpha$ as the disk evolves is most readily explained by grain growth resulting in a shallower frequency dependence of dust opacity.

Understanding the timescales involved in the evolution of circumstellar disks is critical for placing constraints on the dominant mechanism(s) of planet formation. In a purely statistical sense, our large, sensitive, and uniform submillimeter survey of Taurus disks enables a direct comparison with previous work at shorter wavelengths (e.g., Kenyon & Hartmann 1995) to examine the evolution-

ary timescale as a function of disk radius. We found, in general agreement with work at other wavelengths (e.g., Duvert et al. 2000), that only a small fraction of disks, <10%, that have no inner disk signatures of either infrared excess or H$\alpha$ emission were detected in the submillimeter. Based on the disk frequency in clusters of different ages, Haisch et al. (2001) estimate a lifetime for the inner disk of $\sim 5-10$ Myr. The outer disk must therefore become undectable no later than a few $10^5$ yr after the inner disk disappears. Understanding the trigger for this rapid transition remains a key problem in disk evolution. Some possible explanations for the essentially radially independent disk dissipation timescale include viscous accretion with simultaneous photoevaporation by the central star (e.g., Clarke et al. 2001), rapid grain growth at all radii in the early stages of planet formation (e.g., Weidenschilling & Cuzzi 1993), or (more speculative but most intriguing) dynamical clearing by migrating proto-planets.

## 3. Submillimeter interferometry of the Orion proplyds

Given that most low mass stars are born in OB associations (McKee & Williams 1997), it is essential to understand their formation in such an environment. As the statistics of extrasolar planetary systems become better understood (e.g., Marcy, Cochran, & Mayor 2000), it is also natural to extend this question to the formation of planets around low mass stars in massive star forming regions.

The Trapezium cluster in Orion is the nearest young, massive star forming region and it is consequently the most intensively studied (e.g., O'Dell 2001). There are approximatly $10^3 \sim 1$ Myr old stars in the central 1 pc of the cluster core (Hillenbrand 1997) but the radiation field is dominated by one O6 star, $\theta^1$ Ori C. Ionized gas from the evaporating envelopes and disks around nearby low mass stars can be observed at centimeter wavelengths with the VLA (Churchwell et al. 1987) through the optical, most spectacularly with HST (beginning with O'Dell, Wen & Hu 1993).

The HST images provide some of the most dramatic images of protostellar disks that exist (see in particular Bally et al. 1998a). They were dubbed "proplyds" by O'Dell as they were presumed to be protoplanetary on account of their solar system scale sizes. However their masses – and potential for forming planets – were unknown. Only a lower limit less than a Jupiter mass could be obtained by integrating a minimal extinction over their area (McCaughrean et al. 1998) and it was not clear, therefore, that the proplyds had enough mass to form (giant) planets.

Disk masses are best measured at longer wavelengths where the dust emission becomes optically thin. Interferometry is essential to resolve the tightly clustered proplyds from each other and also to filter out the strong emission from the background molecular cloud. Mundy, Looney, & Lada (1995) used the BIMA interferometer at $\lambda 3.5$ mm to image a field around $\theta^1$ Ori C containing 33 proplyds. Several significant peaks were found, four coincident with proplyds, but the intensity was consistent with free-free emission from ionized gas and they were unable to measure masses. By analyzing the non-detections, however, they were able to place a statistical upper limit of 0.03 $M_\odot$ on the average disk mass. The dust emission increases at shorter wavelengths and the free-free emission decreases. Using the OVRO array, Bally et al. (1998b) imaged two fields

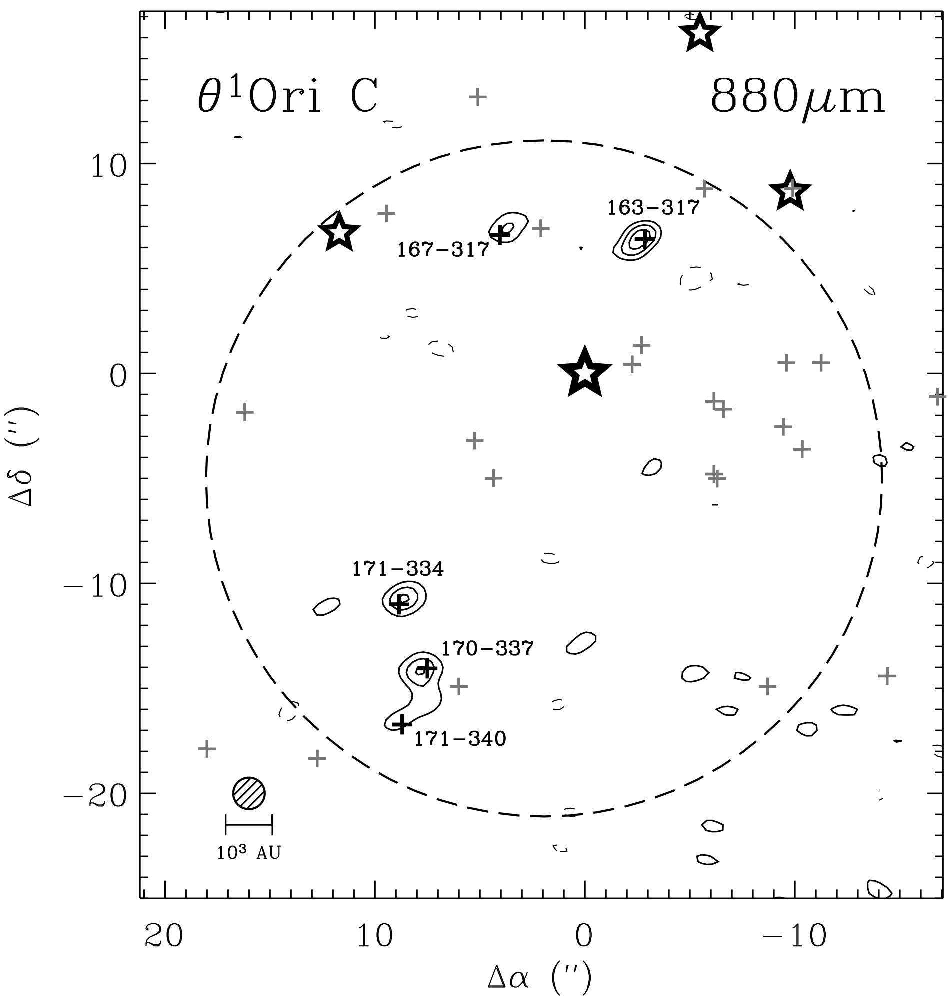


Figure 4. Contours of 880 $\mu$m continuum emission toward the proplyds in the Trapezium cluster. The locations of the proplyds from O'Dell & Wen (1994) are shown by crosses and the five detections are labeled following their nomenclature. The position of the four Trapezium O stars are shown by the large star symbols and the center of the coordinate grid has been set to $\theta^1$ Ori C. The 1.5″ synthesized beam and scale bar are shown in the lower left corner, the large dashed circle is the FWHM of the primary beam. Contour levels are at $3, 5, 7 \times \sigma$ where $\sigma = 2.7$ mJy beam$^{-1}$ is the rms noise level in the map.

containing a total of six proplyds at $\lambda$1.3 mm, made a tentative detection of one object with a mass equal to 0.02 $M_{\odot}$, and placed upper limits of 0.015 $M_{\odot}$ on the other objects. Lada (1999) presented a mosaic of two fields at $\lambda$1.3 mm with the Plateau de Bure interferometer that claimed three detections. The implied masses were $\sim 0.01$ $M_{\odot}$ but these have not been analyzed in detail.

By operating at shorter wavelengths than the other interferometers, the Submillimeter Array (SMA; Ho et al. 2004) is better suited to measuring the dust emission above the strong bremsstrahlung emission from the ionized gas. Furthermore, it has a relatively large field of view which allows many proplyds to be imaged simultaneously.

Details of the observations and their analysis are in Williams, Andrews, & Wilner (2005). We observed a single field toward the center of the Trapezium cluster at 340 GHz (880 $\mu$m). 23 proplyds were contained within the $32''$ full width half maximum primary beam. The resolution of these compact configuration data was $1.5''$ and the rms noise level was $\sigma = 2.7$ mJy beam$^{-1}$.

Contours of the continuum emission are shown in Figure 4. Five proplyds were detected within the $32''$ FWHM of the primary beam with a peak flux greater than $3\sigma = 8.1$ mJy beam$^{-1}$ and are labeled in the Figure. 167–317 ($\theta^1$ Ori G) is a very bright source in the optical and radio. Based on an extrapolation of its SED at centimeter wavelengths (Garay, Moran, & Reid 1987), we appear to be detecting the bremsstrahlung emission from its ionized cocoon even at these short wavelengths. The four other proplyds have fluxes that are significantly above the bremsstrahlung extrapolation and we attribute the bulk of the SMA flux to thermal dust emission.

The corresponding disk masses for these four proplyds, after correcting for a contribution from ionized gas, range from 1.3 to $2.4 \times 10^{-2}\ M_\odot$. These are similar to the minimum mass solar nebula (Weidenschilling 1977). Photoevaporative mass loss rates are high, $\sim 10^{-7}\ M_\odot$ yr$^{-1}$ (Churchwell et al. 1987), but concentrated in the outer parts of the disks where the gravitational potential of the central star is weakest and photoevaporation is most effective (Hollenbach et al. 2000). The radius of the bound inner region depends on the stellar mass and whether the gas is ionized by EUV photons or remains neutral and only heated by the FUV radiation field. The detected proplyds lie far enough away from $\theta^1$ Ori C for the second condition to apply and the central $\sim 20 - 50$ AU radius of the disks survive (Johnstone et al. 1998). Disk radii, measured from the HST observations, are $\sim 40$ AU for the detections so, at most, only the outer 50% of the disk will be lost. For a surface density $\Sigma \sim r^{-3/2}$, the surviving mass fraction is at least 60%. In these systems at least, the submillimeter emission indicates there is sufficient material bound to the star to form Solar System scale planetary systems.

There are intriguing possibilities for the non-detections too. We found a statistically positive flux toward the 18 proplyds that lay below our $3\sigma$ detection limit. The corresponding (gas + dust) mass limit is $8 \times 10^{-4}\ M_\odot$ and the dust-only mass limit is therefore $8 \times 10^{-6}\ M_\odot \simeq 3\ M_\oplus$. That is, even if all the gas were lost from these disks, there would still be enough material to form terrestrial-like planets. Far more sensitive observations would be required to verify this on an individual basis, of course, and it would also be important to average the VLA data in a similar way to measure the low level bremsstrahlung emission.

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## References

Adams, F. C., & Shu, F. H. 1986, ApJ, 308, 836
Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788
Andrews, S. M., & Williams, J. P. 2005, ApJ, 631, 1134
Bally, J., Sutherland, R. S., Devine, D., & Johnstone, D. 1998a, AJ, 116, 293
Bally, J., Testi, L., Sargent, A., & Carlstrom, J. 1998b, AJ, 116, 854
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924
Beckwith, S. V. W., Sargent, A. I. 1991, ApJ, 381, 250
Churchwell, E., Wood, D. O. S., Felli, M., & Massi, M. 1987, ApJ, 321, 516
Clarke, C. J., Gendrin, A., & Sotomayer, M. 2001, MNRAS, 328, 485
Dutrey, A., Guilloteau, S., Duvert, G., Prato, L., Simon, M., Schuster, K., & Menard, F. 1996, A&A, 309, 493
Duvert, G., Guilloteau, S., Ménard, F., Simon, M., & DUtrey, A. 2000, A&A, 355, 165
Garay, G., Moran, J. M., & Reid, M. J. 1987, ApJ, 314, 535
Greene, T. P., Wilking, B. A., Andre, P., Young, E. T., & Lada, C. J. 1994, ApJ, 434, 614
Haisch, K. E., Lada, E. A., & Lada, C. J. 2001, ApJ, 553, L153
Hillenbrand, L. A. 1997, AJ, 113, 1733
Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, ApJ, 616, L1
Hollenbach, D. J., Yorke, H. W., & Johnstone, D. 2000, Protostars and Planets IV, 401
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Johnstone, D., Hollenbach, D., & Bally, J. 1998, ApJ, 499, 758
Lada, C. J., & Wilking, B. A. 1984, ApJ, 287, 610
Lada, E. A. 1999, NATO ASIC Proc. 540: The Origin of Stars and Planetary Systems, 441
Lee, C. W., Myers, P. C., & Tafalla, M. 1999, ApJ, 526, 788
Looney, L. W., Mundy, L. G., & Welch, W. J. 2000, ApJ, 529, 477
Marcy, G. W., Cochran, W. D., & Mayor M. 2000, Protostars and Planets IV, 1285
McCaughrean, M. J., et al. 1998, ApJ, 492, 157
McKee, C. F., & Williams, J. P. 1997, ApJ, 476, 144
Mundy, L. G., Looney, L. W., & Lada, E. A. 1995, ApJ, 452, L137
O,Dell, C. R. 2001, ARAA, 39, 99
O'Dell, C. R., Wen, Z., & Hu, X. 1993, ApJ, 410, 696
Osterloh, M., & Beckwith, S. V. W. 1995, ApJ, 439, 288
Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., Roush, T., & Fong, W. 1994, ApJ, 421, 615
Weidenschilling, S. J. 1977, ApJS, 51, 153
Weidenschilling, S. J., & Cuzzi, J. N. 1993, Protostars and Planets III, 1031
Williams, J. P., Andrews, S. M., & Wilner, D. J. 2005, ApJ, 634, 495